REVIEW ARTICLE

Exchange Bias Effect: A Brief Review

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ABSTRACT: After being discovered in 1956, Exchange Bias effect has invoked the interest of many researchers, which apparently increased after emergence of its versatile application related to giant magneto resistance, spintronics and its use in magnetic sensors and as stabilizers in magnetic reading heads. This review primarily focuses on understanding the phenomenon of Exchange Bias Effect and its evolution throughout these years. Here, we have discussed the different combinations of materials that exhibit this effect, the techniques used. In addition to various theoretical models devised till date, different applications and some unresolved problems associated with Exchange Bias Effect.

KEYWORDS: Exchange bias effect, Ferromagnetic, Anti-Ferromagnetic, Azimuthal Dependence

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1. INTRODUCTION

The exchange bias effect means the biasness of some properties of certain materials due the changes in the temperature of the material. In simple words, every material has some response to the applied magnetic field given by a hysteresis loop. When hysteresis loop shifts relative to the zero-field position due to some external causes, this magnetic phenomenon is called Exchange Bias effect. It is caused by coupling of two materials by exchange interaction, leading to ferromagnetism. Therefore, this exchange interaction and shift of hysteresis loop together produces the effect.

First discovered in fine Co particles covered by CoO [1], Fe/FeF_2, or Fe/MnF_2 [3], which are already exhibited some quite interesting effects for the different materials. Extensive research has been done in this field by observing this effect on different materials and by using different experimental techniques. In order to explain the mechanism behind this effect many theoretical models have also been proposed. Nowadays, more complicated materials are under investigations, such as $Fe/LaAlO_3$ or $Pr_{0.67}Sr_{0.33}MnO_3/SrTiO_3$, several new researches have been made in various material such as in alloys and intermetallic compounds and more sophisticated structures, such as nanostructures or multi-layer sandwiches.

To develop a basic understanding of exchange bias effect, in this review we will discuss the present status of this field. We will present the General properties of Exchange Bias system (Section 2), the various theoretical models developed (Section 3), some techniques used (Section 4), exchange bias on different materials (Section 5), applications (Section 6) several interesting open issues (Section 7) and future scope (Section 8).

1.1 Phenomenology of Exchange Bias Effect

It was discovered by Meiklejohn and Bean in 1956 [1]. They carried out the experiment in which Co particle was embedded in the antiferromagnetic oxide CoO as an interface. Then the system was cooled from room temperature down to 77K through the Néel temperature of CoO [T_N (CoO) = 291K], Displacement of the hysteresis loop was observed.

Earlier the hysteresis loop was symmetrically centered on zero value of the applied field, which is the general behavior of the ferromagnetic material. But when the sample was cooled in a positive magnetic field, the hysteresis loop displaced to negative value. Even when the extremely high field was applied to the sample such displacement did not disappear [1].

The displacement of magnetic hysteresis loop resulting from the pinning effect at the interface between soft and hard magnetic substances has

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let to various experimental evidences that describe the phenomenology of exchange bias effect [1].

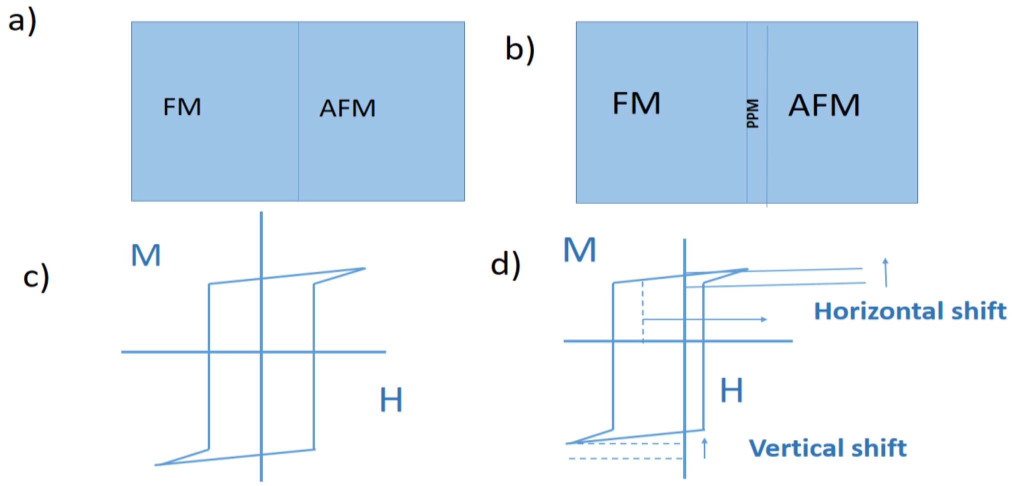

Figure 1: Schematic representation of EB effect due to field cooling in (a) bilayer Ferromagnetic (FM)/Antiferromagnetic (AFM) structure and (b) appearance of a new (PFM) layer at the interface(c) no shift and (d) loop shifts

The Ferromagnetic (FM)/Antiferromagnetic (AFM) bilayer structure is shown in Figure 1(a). When the sample is cooled in a static field through T_N from temperature, $T_N< T < T_C$ down to low temperature ($T \ll T_N$), a new layer appears at the interface [Figure 1(b)]. In most well-studied ferromagnet /antiferromagnet bilayers the Curie temperature of the ferromagnet is larger than the Néel temperature T_N of the antiferromagnet. This inequality means that the direction of the exchange bias can be set by cooling through T_N in the presence of an applied magnetic field. The moment of the magnetically ordered ferromagnet will apply an effective field to the antiferromagnet as it orders; breaking the symmetry and influencing the formation of domains Figure 1(b).

A sample of FM and AFM substances is exposed to a static magnetic field during cooling process. Now, the displacement of magnetic hysteresis loop can be demonstrated through the horizontal and vertical shifts. The horizontal shift provides HE whereas vertical shift of hysteresis loop provides ME [Figure 1(d)]. The shift is absent when the sample is cooled in zero-field as [Figure 1(c)]. It can be concluded that the exchange bias effect is caused by ferromagnetic unidirectional anisotropy formed at the interface between different magnetic phases. Generally, the process of field cooling is used to obtain ferromagnetic unidirectional anisotropy in different types exchange bias systems. Though, large exchange bias has been reported (by Wang et.al., 2011) after zero-field cooling from a unmagnetized state [4].

1.2 Intuitive Picturization of Exchange Bias Effect

Exchange Bias Effect is an interface phenomenon, in order to understand how it originates; an intuitive picturization of the changes at the interface is required. Unidirectional anisotropy and exchange bias can be understood by assuming an exchange interaction taking place at the AFM-FM interface.

When a field is applied in the temperature range of $T_C>T>T_N$ the FM spins line up with the applied field while the AFM spin still stays random [Fig.2(i)]. When cooling is done at $T<T_N$ in the presence of the field, AFM spins align ferromagnetically to FM (assuming ferromagnetic interaction) due to the interaction at the interface. The other spin planes in the AFM arrange in such a way that they produce zero magnetization [Fig.2(ii)]. When the field is reversed, the FM spins start to rotate, but AFM spins remain unchanged [Fig. 2(iii)]. As a result, the FM spins aligns ferromagnetically with the AFM spins at the interface. Therefore, the anisotropy is unidirectional.

The field needed to reverse completely as an FM layer will be larger if it is in contact with an AFM. However, once the field is rotated back to its original direction, the FM spins starts to

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rotating at a smaller field, as a result of the interaction with the AFM spins (reverse of the previous case) (Fig.2(v)] The material now behaves as if there is another internal biasing field, leading to the shift in resultant hysteresis loop.

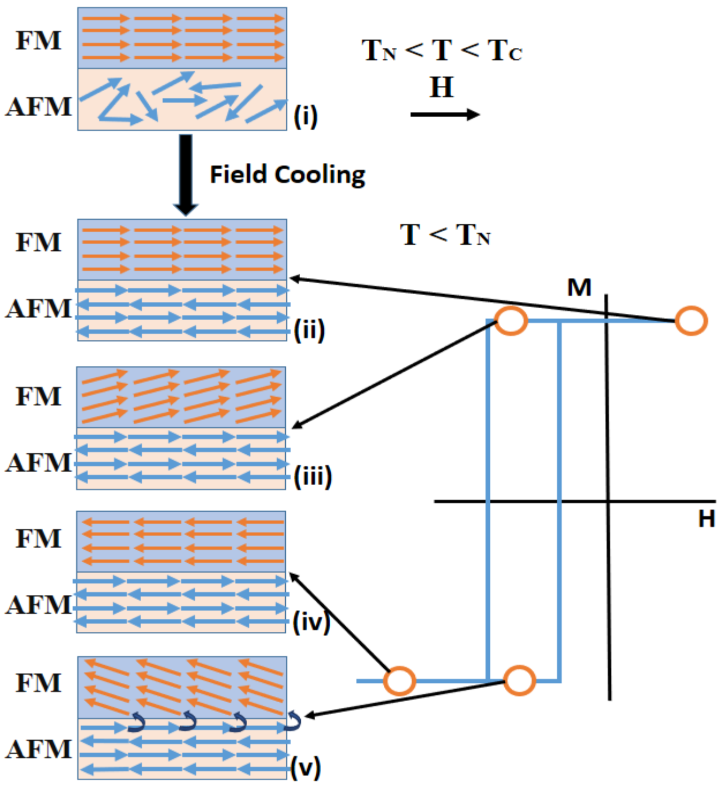

Figure 2: Schematic diagram of the spin configuration of an FM-AFM bilayer at different stages (i to v) and the resulting configuration of hysteresis loop.

It has to be kept in mind that this explanation provides only an intuitive picture of the phenomenon. There are several other microscopic factors like roughness, spin configuration, orientation that govern this effect. A comprehensible view of exchange bias at the microscopic level has not been achieved yet.

2. FACTORS AFFECTING EXCHANGE BIAS EFFECT

Many researchers have been done on exchange bias effect, bringing into light various parameters on which exchange bias effect depends. Also, theoretical models have been developed during the past years that had contributed towards knowing the properties of Exchange Bias Effect in a better way.

The exchange bias is found to be temperature-dependent. The EB field is reduced with increasing temperature and vanishes at the blocking temperature whose range varies from a value much lower than the Néel temperature to a value closer to Néel temperature depending on the material. Besides, the blocking temperature is also influenced by the FM/AFM interface and the structural order in the AFM [8,9].

It has also been found that the exchange bias depends on the thickness of ferromagnetic layer, giving an antiproportional correlation [9,12]. The AFM thickness can have different impact on the exchange bias, considering the material system and the technique used, but in general sense on decreasing the thickness of the AFM, the exchange bias field increases. Néel predicted that in order to produce the hysteresis shift minimum antiferromagnetic thickness is required [9]

The interface roughness is also a very important factor, although it is not consistent with the developed models in many cases. Generally, smooth interfaces of AFM crystals result in a small exchange bias, while rougher interfaces show an increased EB. Contradicting this, many thin film systems reported larger EB

for smoother interfaces and reduced EB when the roughness increases. In addition to this, it has also been found that the level of effect starts increasing again after being minimum at medium roughness [10,11].

Interface orientation also plays an important role in exchange bias effect. In the case of antiferromagnet FeF_2 the spin is oriented in the (110) plane, i.e. perpendicular to the (001) plane. For an interface orientation along the (110) plane observed effect is maximum, for a (101) orientation, average value is observed. The effect is almost zero for a (001) interface [9].

There has been study on the modification of the exchange bias effect also which can be done by the irradiation of He ion. At room temperature FeNi/FeMn exchange bias samples with large exchange bias field is prepared on a Cu buffer layer and when they are irradiated with the He ion. In that case, there is a modification in the both exchange bias field. Actually when the irradiation of ion decreases exchange bias field increases and when the irradiation increases exchange bias field decreases.

Table 1: Comparison of trends of Exchange Bias Effect in different properties

Property	Value	Change in Exchange Bias Effect
Temperature	Increases	decreases
	At blocking temperature	Becomes zero
Thickness of Material	Decreases	Increases
	Minimum	Maximum Hysteresis shift obtained
Roughness*	Increases	Increases
	Decreases	Decreases
	Medium	Minimum
Orientation	(110)	Maximum
	(101)	Average
	(001)	Minimum

2. THEORETICAL MODELS FOR EXPLAINING EXCHANGE BIAS EFFECT

Exchange Bias effect depicts many properties, some of which are often found to be contradicting with one another. Hence, explaining all the properties by one model is difficult, especially as different effects are found in different material systems.

That is the reason why, after the first intuitive models, several other models emerged, aiming at explaining as many experimentally observed effects as possible in a physically reasonable way. Naturally, with new experimental findings, new contradictory factors discovered and new models were required.

In this section, we will take look at all important models proposed so far and their key features.

3.1 Meiklejohn – Bean Model

The first attempt to develop an intuitive model for EB was done by Meiklejohn [15]. In their early and intuitive model, Meiklejohn and Bean assumed coherent rotation of two coupled macro spins describing the F layer and AF uncompensated layer. They suggested that the shift in the hysteresis loop is due to the large anisotropy in the antiferromagnet and weaker exchange energy coupling the ferromagnet and antiferromagnet.

Following are the assumptions made to carry out the result:

- ✓ As a whole, the layer of the ferromagnet rotates rigidly.
- ✓ Both the F and the AF are in a single domain state.
- ✓ The interface of the AF/F is atomically smooth.

- ✓ The layer of the AF is magnetically rigid, means that during the rotation of the F spin the spin of the AF remains the same.
- ✓ The AF interface spin are fully uncompensated: the interface layer has a net magnetic moment.
- ✓ The layers of the AF and F are coupled by an exchange interaction across the F/AF interface. J_{eb} is the parameter assigned to this interaction is the interfacial exchange coupling energy per unit area;
- ✓ The layer of the AF has an in-plane uniaxial anisotropy.

Table 2: Different types of Theoretical Models

Model	Features	Main Result	Drawbacks
Meiklejohn-Bean Model[a]	Coherent F and AF magnetization rotation	H_E much larger than observed experimentally	Results were contradicted
Néel Model[b]	Continuum approximation	Domain wall in the AF, requires large width of the F slab	approximation requires minimum width of the slabs to be valid
Malozemoff's Random Field Model[c]	Random defects create random fields	Reasonable HE values which depend on defect concentration	Not consistent with experiments
Mauri's Model[d]	F interface coupling; thin F film	Reasonable H_E values	Anisotropy constant needs to be small,
Orthogonal F and AF magnetization Model[e]	Canting of the AF Interface spins	Realistic interface Magnetic structure	failed to yield unidirectional anisotropy
Generalized random Interface models[f]	Rough interface; Dipolar interaction is included	finite coercivity, dependent on interface defect	entirely depends on assumption of a rough interface

[a][15], [b] [13], [c][55], [d] [16], [e][56], [f][57,58]

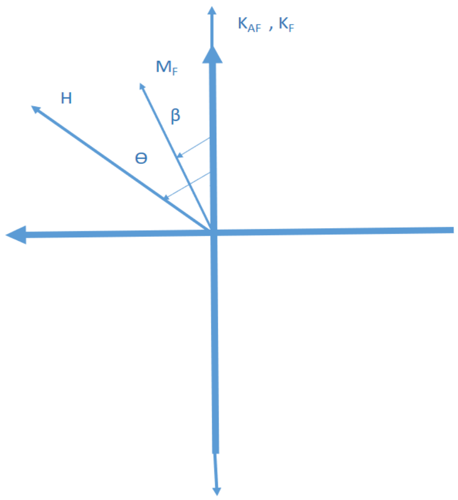

Figure 3: Schematic representations of the angles and vector in Meiklejohn and Bean Model

Here, H is the applied magnetic field making angle ϴ with respect to the field cooling direction denoted by ϴ = 0, K_F and K_{AF} = the uniaxial anisotrophy directions of the AF and F layers. They are assumed to be oriented parallel to the field cooling direction and M_f= the magnetization orientation of the F spins during the magnetization reversal.

The spins of the AF defined during the field cooling process are assumed to be fixed to their orientation. In the analysis below the angle (ϴ =

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0) it is assumed that the applied field is parallel to the field cooling direction. This condition gives the direction along which the hysteresis loop is measured. For the torque measurements and for measuring the azimuthal dependence of the exchange bias fields the angle is $\Theta \neq 0$.

The energy per unit area assuming coherent rotation of the magnetization within this model can be written as:

$E_A = -\mu_0 H M_f t_F \cos(-\beta) + K_F t_F \sin^2(\beta) - J_{eb} \cos(\beta)$ (1)

Where, J_{eb} [J/m^2] is the interfacial exchange energy per unit area M_F is the saturation magnetization of the ferromagnetic layer.

The interfacial exchange energy can be also expressed in terms of exchange interactions:

$E_{int} = \sum_{ij} J_{ij} S_i^{AF} S_j^F$ where summation includes all interactions within the range of the exchange coupling.

$\partial E_A / \partial \Theta = 0$, the stability condition has two types of solutions: one is $\beta = \cos^{-1}[(J_{eb} - \mu_0 H M_F t_F) / (2K_F)]$ for $\mu_0 H M_F t_F - J_{eb} \leq 2K_F$; the other one is $\beta = 0, \prod$ for $\mu_0 H M_F t_F - J_{eb} \geq 2K_F$, corresponding to positive and negative saturation, respectively. The coercive field H_{c1} and H_{c2} are extracted from the stability equation above for $\beta = 0, \prod$:

$$H_{c1} = \frac{-2K_F t_F + J_{eb}}{\mu_0 M_F t_F} \quad (2)$$

$$H_{c2} = \frac{2K_F t_F - J_{eb}}{\mu_0 M_F t_F} \quad (3)$$

By using the above equation, the coercive field H_c of the loop and the displacement H_{eb} can be the calculation according to:

$$H_c = \frac{2K_F}{\mu_0 M_F t_F} \quad (4) \text{ and}$$

$$H_{eb} = \frac{-J_{eb}}{\mu_0 M_F t_F} \quad (5)$$

The above equation (5) is the main formula of the exchange bias effect. For an ideal case the expected characteristics of the hysteresis loop is given by this formula. It predicts that the sign of the exchange bias effect is negative. However, there are some exceptions as positive exchange bias was observed for CoO/Co, $Fe_xZn_{1-x}F_2$/Co and $Cu_{1-x}Mn_x$/Co bilayers when the measuring temperature was close to the blocking temperature. Positive exchange bias effect was also observed in Fe/FeF_2 and Fe/MnF_2 bilayers. The above equation also predicts that the exchange bias effect is inversely proportional the thickness of the ferromagnet:

$$H_{eb} \approx \frac{1}{t_f}$$

From equation (4) it is shown that the coercivity of the magnetic layer is the same with and without exchange bias effect. But this is contradiction to the experimental observations. Usually it is observed that the coercive field increases.

3.2 The Néel Model

Néel et al., [13] developed a model that applied to a system which consists of a weakly anisotropic uncompensated AF layer ferromagnetically coupled across the interface to an F slab. The authors adopted the theoretical approach of MB Model by introducing the concept of planar domain wall forming during the magnetization reversal.

The rigid AF spin state and rigidly rotating AF spins, both the concepts impose restrictions on the behavior of the antiferromagnetic spins that the AF order is preserved during the magnetization reversal. This restriction states that the interfacial exchange coupling is found almost entirely in the hysteresis loop either as a loop shift or as coercivity. Experimentally, but the size of the exchange bias does not agree with expected value as it is lower of several order than the expected value. A partial domain wall is assumed to be developed in the AF layer during the magnetization coupling in order to avoid the loss of coupling energy. Neel introduced this concept by considering the coupling between the ferromagnet and a low anisotrophy antiferromagnet. An important fraction of the exchange coupling energy, lowering the shift of the hysteresis loop will be stored by the AF partial domain wall.

With the help of a differential calculation the magnetization orientation of each layer has been calculated by Neel. The week coupling, which is parallel to the interface wall, is consistent with the partial domain wall. A minimum AF thickness is required to produce hysteresis shift is predicted by this model; for example, a ferromagnetic iron slab in excess of 1000A° is needed [14].The concept of the partial domain wall forms the basis for further models which comprises either Neel wall or

Bloch wall formation as a way to reduce the observed magnitude of exchange bias.

Thus, while the Néel model is an important milestone, its use in the better characterized thin film EB systems developed recently is quite restricted and has to be implemented with caution.

3. Malozemoff Random Field Model

Malozemoff in 1987, proposed a model of exchange anisotropy based on the assumption of rough F/A compensated and uncompensated interfaces [55]. He discarded the assumption of a perfectly uncompensated and smooth interface and considered an imbalance of the interfacial antiferromagnetic moments as a result of roughness and structural defects.

He postulated a random nature of exchange interaction at the F-FA interface. It was assumed by him that the chemical roughness or alloying at the interface causes lateral variations of the exchange field acting on the F and AF layers which is present for any realistic bilayer system. Due to the energy minimization the resultant random field causes the AF to break up into magnetic domain. The Malozemoff's approach belongs to models on the mesoscopic scale foe surface magnetism which in contrast with other theories, where the unidirectional anisotropy is treated either microscopically or macroscopically.

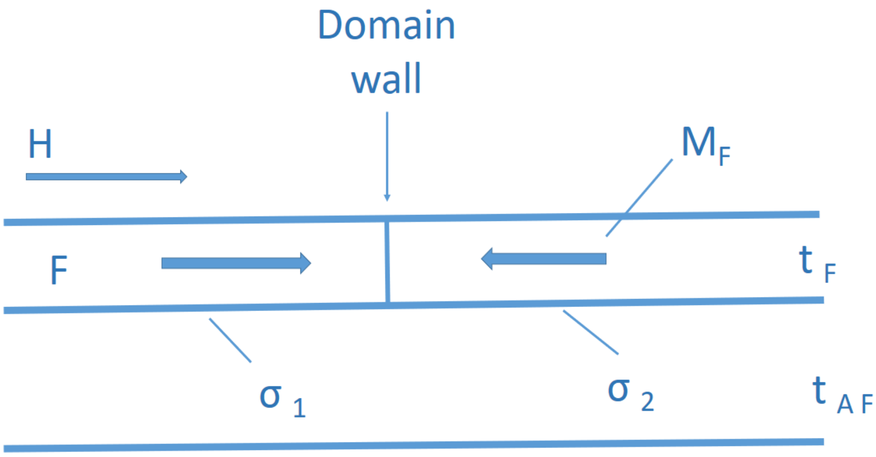

Figure 4: Schematic side view of a F/AF bilayer with ferromagnet wall due to an applied field H

Figure 4 shows the general idea for estimating the exchange bias anisotropy, where the domain wall in an uniaxial ferromagnet that is driven by an applied in–plane magnetic field H. considering that the interfacial energy in one domain (σ_1) is different from the energy in the next domain (σ_2), then the exchange bias can be determined by the equilibrium condition between the applied field pressure $2HM_Ft_F$ and the effective pressure from the interfacial energy $\Delta\sigma$:

$$H_{eb} = \frac{\Delta\sigma}{2M_F t_F} \quad (7)$$

Where, M_F and t_F are the magnetization and thickness of the ferromagnet. The exchange bias is zero when the interface is treated as ideally "compensated". While if the AF/F interface is ideally uncompensated there is an interfacial energy difference $\Delta\sigma = 2J_i/a^2$, where J_i is the exchange coupling constant across the interface, and a lattice parameter of a simple cubic structure assigned to the AF layer. The EB field is given by the equation

$$H_{eb} = \frac{J_i}{a^2 M_F t_F} \quad (8)$$

Evaluating numerically the size of the EB field using the equation above (7) for an ideally uncompensated interface, results in a difference of several orders of magnitude with respect to the experimental observation. In order to reduce the resulting exchange bias field drastically a novel mechanism based on random field at the interface acting on the AF layer is proposed. Malozemoff describes how the roughness on the atomic scale of a "compensated" AF interface layer can lead to uncompensated spin required for the loop to shift.

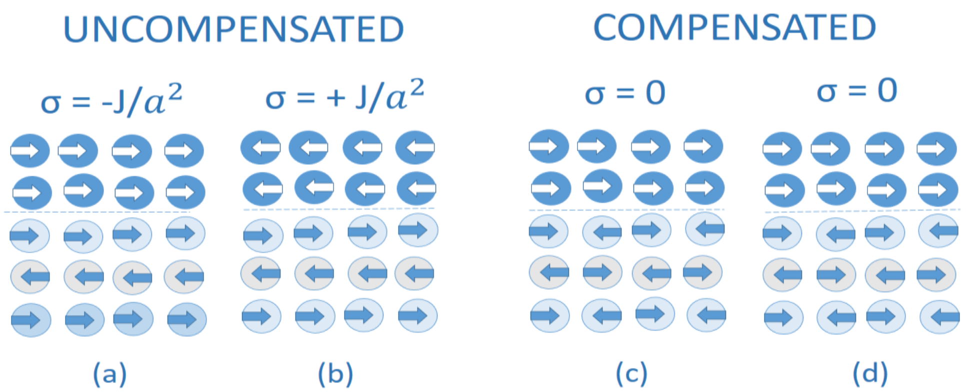

Figure 5: (a) represents the uncompensated configuration, (b) represents the configuration when the ferromagnetic spins are reversed, (c) represents the compensated configuration and (d) represent the configuration when the direction is reversed.

In the Figure 5(b) a bump shifted by one lattice spacing, which is equal to reversing the F spins, provides six net ferromagnetic deviations from perfect compensation. Therefore a net energy difference of $_{zi}J_i$ with z_i = 12 acts at the interface favouring one domain orientation over the other.

When reversing the field spins the energy difference is only $8J_i$ for an ideally uncompensated interface. This estimated that the roughness of the atomic step at a compensated interface leads to a higher exchange bias as compared to the ideally compensated interface. By considering the more detailed model the calculation of this local field can be further refined. For example, by changing the direction of the spin in the bump as shown in Figure 5(c) the difference in the energy of the interface is reduced by 5× $2J_i$ at the cost of generating one frustrated pair in the AF layer just under the bump. The energy difference of $2J_A$ is generated by this frustrated pair where, J_A is the AF exchange constant. Therefore the energy difference between the two domains becomes $2J_i + 2J_A$ or roughly 4J if $J_i \approx J_A \approx J$. If the localized canting of the spins is allowed then there is a further decrease in the energy difference.

The irregularity of each interface will give a local energy difference between domains whose sign depends upon the particular location of the irregularity and magnitude is on the average 2zJ, where z is the number of order unity. Apart from this, for a random interface on the atomic scale, the local unidirectional interface energy $\sigma_l = \pm zJ/a^2$ will also be random and its average σ in a region L^2 will decreases statistically as $\sigma \approx \sigma_l/\sqrt{N}$, where $N = L^2/a^2$ is the number of sites projected onto the interface plane. Hence, the effective AF-F exchange energy per unit area is given by:

$$J_{eb} \approx \frac{1}{\sqrt{N}} J_i \approx \frac{1}{L} J_i \quad (9)$$

Where, j_i is the exchange energy of a fully uncompensated AF- surface. When the interface roughness gives a random field and a region is assumed to have single domain ferromagnet, then AF break up into magnetic domain (Figure 6)

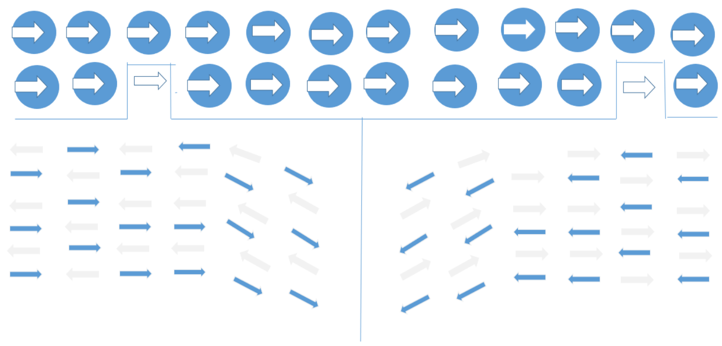

Figure 6: Schematic diagram of a vertical domain wall in the AF layer

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A perpendicular domain wall is most preferable situation and is permanently present in the AF layer. The perpendicular domain wall should be distinguished from the parallel domain wall of AF/F interface, which is developed temporarily during the rotation of the F layer according to the Mauri model on further analyzing the stability of the magnetic domains in the presence of random field, a characteristic length L of the frozen-in AF domains and their characteristic height are obtained:

$L \approx \pi\sqrt{A/K_{AF}}$ and h = L/2, where A_{AF} is the exchange stiffness and h is the characteristic height of the AF domains. When these domains are fixed, flipping the ferromagnetic orientation causes an energy exchange per unit area of $\Delta\sigma = 4zJ/\pi al$, gives the expression of the exchange bias field as shown below

$$H_{eb} = \frac{2z\sqrt{AK_{AF}}}{M_F t_F \pi^2} \quad (10)$$

Considering CoO/Co (100 A°) the calculated exchange bias using the equation is (8) is 580 Oe, the following values for the exchange stiffness are used according to the above estimations: $A_{AF}=J_{AF}/a$, where a is the lattice parameter of CoO and J_{AF} = 1.86 meV is the exchange constant for CoO. Then for CoO the characteristic length of the AF domains is given by the formula $L=\pi\sqrt{A/K_{AF}}$ and we get the value 16.6 A°. The height of the AF domains is h = L/2 =8.3 A°.

On comparing this value to the experimental data on CoO/Co, It was estimated that the calculated value of the EB field agrees well with the experimentally observed value. And also there is no enough space for the development of the length and height of the AF domain. There is a difference between the theory and experiment that experimentally AF domains can occur and vary size and orientation after the very first magnetization reversal; however during the field cooling procedure the AF domains are assumed to develop within the Malozemoff model.

4. Mauri Model

Mauri et al. [16] proposed a mechanism of formation of a planar domain wall at the interface as the ferromagnet rotates. Depending on the domain wall energies, the domain wall could be formed in the ferromagnet or in the antiferromagnet. Interestingly, the exchange bias field calculated within this model was the same as in the historical model of Meiklejohn and Bean who used single-domain.

In Mauri's model the domain state of both the F and AF is single, the F layer has a rigid rotation, domain wall developed by the AF layer is parallel to the interface, the interface layer of the AF is uncompensated and anisotrophy of the AF is uniaxial.

There is a coherent rotation of the F spin when the magnetic field is to measure the hysteresis loop. The direction of the first interfacial monolayer of AF is away from the F spin that make an angle α with the field cooling direction and with the anisotropy axis of the AF layer. The second monolayer of the AF is directed away from the interfacial AF spin in order to form a domain wall parallel to the interface. The spin only one AF sub lattice is obtained while the spin of the other sub lattice is in opposite direction in order to complete the AF order (Figure 7)

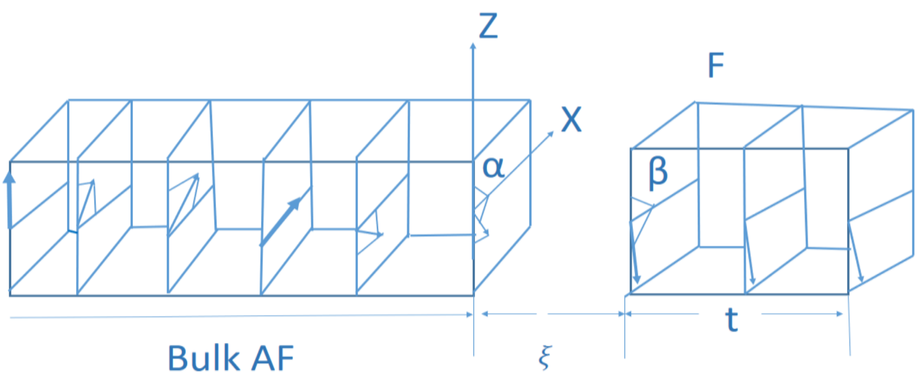

Figure 7: The schematic representation of the mauri model for the interface of the thin ferromagnetic film on an antiferromagnetic film

The total magnetic energy can be obtained by using the Stoner-Wohlfarth model, which can be written as:

$E = -\mu_0 H M_F t_F \cos(\Theta-\beta) + K_F t_F \sin^2(\beta) - J_{eb} \cos(\beta-\alpha) - 2\sqrt{(Ak)}_{AF}(1-\cos(\alpha))$, (11)

Where first part represents the Zeeman energy of the ferromagnet in the given magnetic field, the second part represent the anisotropy term of the F layer, the third part represent the exchange energy of the interface and the fourth part represent the energy of the partial domain wall. The exchange of stiffness is the new notation in the above equation i.e. A_{AF}. The magnetization curve was calculated by the Mauri et al from the numerical minimization of the reduced total magnetic energy from the equation given below:

$e = K(1-\cos(\beta) + \mu\cos(\beta)^2 + \lambda[1-\cos(\alpha-\beta)] + (1-\cos(\alpha))$ (12)

In order to get the authentic hysteresis loop λ and μ of various values were considered. Two limiting cases were obtained by the analysis from the given exchange bias field expression:

$$H_{eb} = \begin{cases} \dfrac{-A_{12}/\xi}{\mu_0 M_F t_F} (1: & for\ \lambda \ll 1 \\ \dfrac{-2z\sqrt{AK_{AF}}}{\mu_0 M_F t_F} & for\ \lambda \gg 1 \end{cases}$$

In case, $\lambda \ll 1$, for the strong coupling limit the exchange bias field values are the same as obtained in the Meiklejohn and Bean model. According to this case there is no difference between the assumption of the both the model. But in the case of $\lambda \gg 1$, for the weak coupling a reduced exchange bias field is given by the Mauri model which is independent of the interfacial exchange energy which is dependent on the energy of the domain wall and the parameters of the F layer. In both case the "$1/t_f$" is preserved the Mauri model.

However, this model has many drawbacks like in order to develop a domain wall in the AF, the anisotropy constant needs to be quite small; otherwise it is energetically favourable for the domain wall to form in the F side as inferred experimentally by Fitzsimmons et al., [17], Dahlberg et al., [19] and many others.

3.5 Koon's Spin Flop Coupling at Compensated Interfaces

In 1997, Koon established that the ground state configuration corresponds to perpendicular orientation of the bulk F moments relative to the AF magnetic easy axes direction, on the basis of a Heisenberg model [56]. However; it failed to yield unidirectional anisotropy.

3.6 Random Interface Field Model

Schulthess and Butler [57,58] showed that Malozemoff's random interface field and Koon's orthogonal magnetic arrangement, rather than being in conflict, could be combined to provide an explanation of EB. However, there is a limitation that the model entirely depends on the assumption of a rough interface, and the results depend on the nature and concentration of the interface defects that are incorporated in the system.

4. EXPERIMENTAL METHODS USED IN OBSERVING EXCHANGE BIAS EFFECT

So far, various experimental techniques have been used to investigate Exchange bias and related effects. The most commonly used techniques and the main information they provide are summarized.

4.1 Magnetization

Hysteresis loops, obtained from magnetization versus applied field, is the most commonly used technique to study exchange bias materials. These Hysteresis loops have been measured by variety of instruments such as SQUID [32,33], vibrating sample magnetometer (VSM) [28,34] and loop tarcers [35-37]. The main information obtained from these techniques is the loop shift and coercivity it also provides information about anisotropies based on the shape of the hysteresis loops.

4.2 Torque magnetometer

Using Torque magnetometer, magnetization is measured while rotating the sample in a field; this gives information about the anisotropies present. The presence of a sin component in the torque depicts the fact that anisotropy in unidirectional in this case. The first model of exchange bias effect by Meiklejohn and Bean was based on this experimental method.

4.3 Neutron diffraction

Due to the magnetic nature of the neutrons, neutron diffraction is the ideal probe for the magnetic structure in addition to the physical structure.

The results of this technique are a bit different. Generally, FM-AFM systems form domains in the FM or AFM layers, but in this case, they do not form domains in FM or AFM layers. To enhance the diffraction signal in neutron diffraction often multilayers of the type [FM-AFM] are investigated. [38-41]. The main information obtained from this method is the spin configuration of the different magnetic layers. Other information about domain formation can also be accessed indirectly.

4.4 Domain Observation

FM and AFM domain play an important role in exchange bias effect. The studies have been done using various techniques such as Bitter method, Kerr effect, Lorentz microscopy, Faraday Effect, interface colloidal contrast, spin polarized secondary electron microscopy or magnetic force microscopy (MFM).

The detailed behaviour of the FM domains depends on the AFM-FM system studied and the thickness of the FM film, probably due to the different anisotropies of the AFM and/or FM materials. Due to the hysteresis loop shift, the domain structure always appears at higher fields than for single FM layers. Usually the domain structure in AFM-FM bilayers is more complicated (i.e. more sizes, shapes and types of domains) than for single FM films. The size and morphology of the domains is also system dependent.

4.5 Brillouin scattering

In this method, a laser beam of visible range is made to fall on FM or AFM sample and the scattered light is measured as a function of angles, field and temperature. The changes in the scattered spectrum together with the scattering geometry give information on the spin wave frequency. From the shift of the spin wave frequency, exchange bias is obtained in the saturated state [42].

4.6 Magnetic dichroism

In this technique, the electrons in the sample are excited with X-rays, and the photon energy emitted by the electrons recombining to the ground state is measured as a function of the magnetic field and temperature. The high sensitivity to different elements, allows material specific properties to be studied independently. Moreover, magnetic dichroism can probe the magnetic properties at different depths, allowing the study of buried layers or interfaces

5. EXCHANGE BIAS EFFECT IN DIFFERENT MATERIALS

After its discovery, during the span of 65 years, Exchange Bias effect has been observed on various types of materials depending on shape and properties, depicting different characteristics in each case. In this section, we will briefly summarize the exchange bias effect on different types of materials.

5.1 Small Particles

Exchange bias in small particles has been observed in a number of materials, mainly ferromagnetic particles covered with their antiferromagnetic or ferrimagnetic oxide. Like, Co-CoO [15,43], Ni-NiO [43]. In small particles, it is difficult to determine the exact FM and AFM thicknesses, hence, results between different systems can't be compared consistently. A general trend exhibited by most small particles systems is the existence of non-vanishing rotational hysteresis and an increase of coercivity below T_N. But, only Co-CoO, and Co-CoNi depict large loop shifts.

Moreover, these systems are not ideal for studies of fundamental aspects of exchange bias, because: particle size is distributive in nature and one cannot always determine intrinsic factors that affect this phenomenon.

Table 3: Exchange Bias Effect in different types of small particle system

Material	Loop Shift	Rotational Hysteresis
1. Co-CoO[a]	Large (9500 Oe)	Yes
2. Ni-NiO[b]	Small (400 Oe)	Yes
3. Fe-FeO[c]	Zero	Yes

[a] [15], [b] [43], [c] [43] values in brackets are the maximum values obtained for loop shift

5.2 Non-Uniform Materials

Few materials do not have clearly defined FM-AFM interface. These materials with competing magnetic interactions, where due to the arrangement of the magnetic ions, different areas (or domains) with AFM or FM interactions are created, due to the nature of these materials, it is difficult to extract information about exchange bias. This category comprises spin glasses and some ferrimagnets.

Spin glasses have been thoroughly studied for many years, and are known to exhibit exchange bias properties, like shift in loop [44,45].The most studied systems under spin glass category are alloys containing Mn. In some of the above systems exchange bias properties have been observed in polycrystalline [48,49], single crystal [47] and thin film form [46]. Another important group of spin glasses, which also exhibit exchange bias properties, are Fe and Mn based amorphous materials.

Exchange bias properties have been observed in different types of ferrimagnets such as oxide type ferrimagnets like Co_2TiO_4 of $CoCr_2O_4$ and amorphous rare-earth based alloys like TbFe or GdCo.

5.3 Thin Films

Thin Films happen to be the most widely studied type of system that exhibit exchange bias. Application wise, this the most suitable type of material, but from critical point of view, most of the discrepancy that arises due to thickness or temperature have been observed in this. To compare different systems, the magnitude of the exchange bias is described in terms of interface energy per unit area using the relation

$$\Delta E = M_{\mathrm{FM}} t_{\mathrm{FM}} H_{\mathrm{E}}$$

where M_{FM} is saturation magnetization, t_{FM} is thickness of the ferromagnet and H_{E} isthe magnitude of exchange bias effect.

5.3.1 Oxide AFMs

Following the work on oxidized FM particles, most of the early work on exchange bias on thin films was on oxidized transition metal films, Co-CoO [59,60], Ni-NiO [35,37], Fe-FeO [61,62]. Similar to oxidized particles, oxidized Co films exhibit rather large exchange bias while oxidized Ni and Fe films usually show smaller loop shifts. Well oriented AFM oxides can exhibit smaller exchange bias than oxidized metallic layers or polycrystalline AFM layers (Table 3), probably due to oxidation through grain boundaries, increasing the effective interface area or other magnetic or microstructural factors.

Table 4: Comparison of Interface energy ΔE, blocking temperatures T_B, and Néel temperatures T_N, for oxide AFMs used in exchange bias.

Material	ΔE (erg/cm²)	T_B (K)	T_N (K)
1. (i) NiO (Oxidised)[a]	0.05-0.29	450-480	520
(ii) NiO (Poly)[b]	0.007-0.09	450-500	520
2. (i) CoO (Oxidised)[c]	0.40-3.50	200-290	290
(ii) CoO (Poly)[d]	0.03-0.12	290	290
3. FeO (Oxidised)[e]	0.05-0.10	100	200

[a]AFM layer obtained from the oxidation of Ni layers [35,37]
[b] Polycrystalline AFM layers [66]
[c] AFM layer obtained from the oxidation of Co layers [60,67]
[d]Polycrystalline AFM layers [25]
[e]AFM layer obtained from the oxidation of Fe layers [68]

5.3.2 Metallic AFMs

The first fully metallic thin film system was reported in 1964. $Fe_{20}Ni_{80}$/Mn bilayers were annealed to enhance diffusion, thus creating antiferromagnetic compounds at the interface. There have also been studies on Fe_{50} Ni_{50} [63].

Table 5: Comparison of Interface energy ΔE, blocking temperatures T_B, and Néel temperatures T_N, for metallic AFMs used in exchange bias

Material	ΔE (erg/cm²)	T_B (K)	T_N (K)
1. (i) $Fe_{50}Mn_{50}$ (Poly)[a]	0.02-0.20	390-470	490
(ii) $Fe_{50}Mn_{50}$ (Poly–ann)[b]	0.05-0.47	420-570	490
(iii) $Fe_{50}Mn_{50}$ (111)[c]	0.01-0.19	380-480	490
(iv) $Fe_{50}Mn_{50}$ (100)[d]	0.04-0.07	-	490
(v) $Fe_{50}Mn_{50}$ (110)[e]	0.04-0.06	-	490
2. (i) $Ni_{50}Mn_{50}$ (Poly)[f]	0.002	770	1070
(ii) $Ni_{50}Mn_{50}$ (Poly-ann)[g]	0.16-0.46	770	1070

[a]Polycrystalline AFM layers [28,63]
[b]Polycrystalline AFM layers after annealing [69,70,71]
[c] AFM layers with (1 1 1) texture [72,73,74]
[d]AFM layers with (1 0 0) texture [18,33,75]
[e] AFM layers with (1 1 0) texture [18,33,75]
[f] Polycrystalline AFM layers [76]
[g]Polycrystalline AFM layers after annealing [77,78,79]

5.3.3 Other AFMs

In this category, non-oxides and non-metallic systems are included that exhibit exchange bias effect. In this category, non-oxides and non-metallic systems are included that exhibit exchange bias effect. It includes sulfides, fluorides and nitrides. The first of such systems was FeS [64,65]. Like in oxidized films, it is difficult to compare with other systems since the details of the structure are not clear. Studies on FeF_2 and MnF_2 have been conducted.

Table 6: Comparison of Interface energy ΔE, blocking temperatures T_B, and Néel temperatures T_N, for system having sulphides and fluorides of AFMs

Material	ΔE (erg/cm²)	T_B (K)	T_N (K)
1. (i) FeS (poly)[a]	0.11	540	610
2. (i) FeF_2 (110)[b]	0.5-1.3	79	79
(ii) FeF_2 (101)[c]	0.2-0.4	79	79
(ii) FeF_2(001)[d]	0.002	79	79
3. MnF_2 (110)[e]	0.05	67	67

[a]AFM layer obtained from sulfading Fe layer [64]
[b]AFM layer with (1 1 0) texture [10,80,81]
[c]AFM layer with (1 0 1) texture [10]
[d] AFM layer with (0 0 1) texture [10]
[e]AFM layer with (1 1 0) texture [10]

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5.4 Different shapes of materials

Most of the research on exchange bias effect has been done on flat multilayer or bilayer surfaces. However, there have also been studies for materials in the form of magnetic anti dots and dots (Perzanowski et.al. in 2017 and Suck et. al. in 2009 [50,51], Core-shell nanostructures (Salazar et. al. in 2016 and Shi et. al. in 2014) [52,53] and even in the shape of rings and disks (Stamps et. al. in 2009) [54].

6. UNRESOLVED ISSUES

Even though extensive research has been done in this field, there are many experimental aspects of exchange bias which are yet to be studied in detail; they still remain controversial or unresolved. In this section we discuss some of these issues.

6.1 Thickness
(A) In FM

For all the systems studied, it has been observed that exchange bias is roughly inversely proportional to the thickness of the FM layers [18-20], But this is only true when the thickness is sufficiently large, if very thin FM layer is taken, the relation is no longer valid [21].

(B) In AFM

The dependence of EB on the AFM thickness is more complicated. The general trend is that for thick AFM layers, exchange biasis independent of the thickness of the AFM layer. As the AFM thickness is reduced, it decreases abruptly. For thin enough AFM layers (usually a few nm) the effect becomes zero. Although, major discrepancies have been observed in these trends [22, 18, 23]

6.2 Interface Disorders
(A) Roughness

The characteristics of exchange bias effect on roughness but it has been found that different material show different sensitivity towards it. Hence, no general trend can be formulated on this basis.

(B) Grain Size

The role of the grain size (or AFM coherence length) in exchange bias remains unclear. Some of the effects of the AFM grain size are expected to besimilar to the thickness trends. While exchange bias is reported to increase with increasing grain size for some systems [22,24], but in some cases [25,26] is reported to decrease with increasing grain size.

(C) Impurity layer

It was found that the presence of impurity layers (amorphous or oxidized layers and/or adsorbed C, H or H_2O) at the interface tend to decrease the magnitude of Exchange Bias [28,29].Though there is a systematic study of this effect, few observations have not yet been explained.

6.3 Anisotropy

The simple intuitive models conclude that the exchange bias should be larger for larger AFM anisotropies. However, since the anisotropy of the AFM material and exchange bias depend on the microstructure of the AFM layer, exact quantitative analysis is difficult.

6.3 Compensated – Uncompensated

In a compensated AFM interface the net spin over a microscopic length is zero. Therefore, this kind of surface will have zero net magnetization. In contrast, if the spin arrangement is such that the surface magnetization is non-zero, the surface is uncompensated. It was expected that for compensated surfaces, the spins pinning the FM layer cancel out, giving zero exchange bias effect. However, it was found that all compensated surfaces investigated experimentally, exhibit exchange bias, even in AFM single crystals covered by FM films. Some of these orientations exhibit very large loop shifts, often larger than uncompensated orientations of the same AFM materials. This effect could be due to some kind of spin re-arrangement at the interface which is usually neglected.

7. APPLICATIONS OF EXCAHNGE BIAS EFFECT

Materials exhibiting exchange bias and related effects have been proposed and utilized in several fields. The first proposed application of exchange bias in bilayers was as magnetic recording media. The most advanced disk media are antiferro magnetically coupled. It

uses interfacial exchange to effectively increase the stability of small magnetic particles.

Another proposed application of is as domain stabilizer in recording heads based on anisotropic magneto resistance. Use of exchange bias has also been reported in designing sensors (Negulescu et. al. in 2009) [27], in biomedicine (bIssa et. al. in 2013 and Ehresmann et. al in 2015) [30,31]

Since the discovery of GMR (bringing the discoverers Nobel Prize in Physics, 2007), in exchange bias spin valves many other devices have been proposed like read-heads, magnetic sensors and magnetoresistive memories.

8. SCOPE

With so much research going on in this field, many unexpected results have been found. Like, the spontaneous exchange bias arising due to the first hysteresis loop at low temperatures, an exchange bias in systems not consisting of the typical AFM/FM combinations, and single-phase materials exhibiting exchange bias [60]. These are some topics that provide the scope of future study in this field. In addition to this, systems exhibiting an exchange bias above room temperature are of great technological interest for spintronics and memory devices.

9. CONCLUSION

There are many factors on which exchange bias effect depends. These factors can be intrinsic, e.g. spin orientation or anisotropy, and extrinsic, e.g. roughness or crystallinity. Consequently, the magnitude is a combination of many factors for different materials, and different techniques, which makes its theoretical analysis complicated. Hence, future research in this field should not only concentrate on technologically promising material systems, but also on developing new models to understand the exchange bias effect better, and investigate new systems to enable a deeper knowledge of the same.

REFERENCES

[1] Meiklejohn,W. H., 1962. Exchange Anisotropy - A Review, J. Appl. Phys., 33, p. 1328.

[2] Tillmanns, A., Oertker,S., Beschoten, B., Güntherodt, G., Eisenmenger, J., Schuller I.K., 2008. Angular dependence and origin of asymmetric magnetization reversal in exchange-biased Fe/FeF_2 (110) Phys. Rev. B, 78, 012401.

[3] Macedo, W. A. A., Sahoo, B., Kuncser, V., Eisenmenger, J., Felner, I., Nogués, J., Liu K., Keune, W., Schuller, I.K., 2004. Changes in ferromagnetic spin structure induced by exchange bias in Fe/MnF2 films, Phys. Rev. B,70, 224414.

[4] Wang, B., Liu, Y., Ren, P., Xia, B., Ruan, K., Yi J., Ding, J., Li. X., Wang. L., 2011. Large Exchange Bias after Zero-Field Cooling from an Unmagnetized State,Phys. Rev. Lett. 106, 077203.

[5] Paccard, D., Schlenker, C., Massenet, O., Montmory, R., Yelon, A., 1966. A New Property of Ferromagnetic-Antiferro magnetic Coupling, Phys. Stat. Sol.(b), 16.

[6] Hoffmann, A., 2004.Symmetry Driven Irreversibilities at Ferromagnetic-Antiferromagnetic Interfaces, Phys. Rev. Lett., 93, 097203.

[7] NoguesJ., SortJ., LanglaisV., SkumryevV., SurinachS., MunozJ.S., BaroM.D., 2005. ExcahngeBais in Nanostructures, Physics Reports, 422, 65.

[8] ThomasS., ReethuK., ThanveerT., MyintM. T. Z.,Al-HarthiS. H., 2017.Effect of shell thickness on the exchange bias blocking temperature and coercivity in Co-CoO core-shell nanoparticles,J. Appl. Phys., 122, 063902.

[9] Nogués, J., Schuller, I.K., 1999. Exchange Bias,J. of Magn. Magn. Mater., 192, 203.

[10] Nogués, J., Moran, T. J., Lederman, D., Schuller, I.K., Rao, K. V., 1999. Role of interfacial structure on exchange-biased FeF_2−Fe, Phys. Rev. B, 59, 6984.

[11] Leighton, C., Nogués, Harry Suhl J., Ivan K. Schuller,1999. Competing interfacial exchange and Zeeman energies in exchange biased bilayers,Phys. Rev. B, 60, 12837.

[12] Radu, F., Zabel, H., 2008. Exchange bias effect of ferro-/antiferromagnetic hetero structures, Springer Tracts in Modern Physics, 227, 97-184.

[13] Néel, L., 1967. Etude théorique - du couplage ferro-antiferro magnétique dans les couches minces, Annales de Physique, 14, 61.

[14] Kiwi, M., 2001. Exchange bias theory, J. of Magn. Magn. Mater.,234, 584.

[15] Meiklejohn, W. H. , BeanC. P., 1957.New Magnetic Anisotropy, Physical Review, 105.

[16] Mauri, D., Siegmann, H. C., Bagus, P. S., Kay E., 1987. Simple model for thin ferromagnetic films exchange coupled to an antiferromagnetic substrate,J. Appl. Phys., 62.

[17] Fitzsimmons,M.R., Yashar,P., Leighton,C., Schuller,I.K., Nogués,J., Majkrzak,C.F., Dura,J.A., 2000.Asymmetric magnetization reversal in exchange-biased hysteresis loops, Phys. Rev. Lett., 84, 3986.

[18] Jungblut,R., Coehoorn,R., Johnson,M. T., aan de SteggeJ., Reinders,A., 1994. Orientational dependence of the exchange biasing in molecular-beam-epitaxy-grown $Ni_{80}Fe_{20}/Fe_{50}Mn_{50}$ bilayers, J. Appl. Phys., 75, 6659.

[19] Dahlberg, E.D., Miller, B., Hill, B., Johnsson, B.J., Strom, V., Rao, K.V., Nogués, J., Schuller, I.K., 1998. Measurements of ferromagnetic / antiferromagnetic interfacial exchange energy in CO/CoO and Fe/FeF_2 layer,J. Appl. Phys., 83.

[20] Tsang, C., Heiman, N., Lee, K., 1981. Exchange induced unidirectional anisotropy at FeMn-$Ni_{80}Fe_{20}$ interface, J. Appl. Phys., 52, 2471.

[21] Parkin, S.S.P., Speriosu, V.S., Mejõa-Lira, F., Moran-Lopez, J.L. (Eds.), 1990. Magnetic Properties of Low-Dimensional Systems II, Springer, 110.

[22] Tsunoda,M., Tsuchiya,Y., Konoto,M., Takahashi,M., 1997. Microstructure of antiferro magnetic layer affecting on magnetic exchange coupling in trilayered Ni-Fe/25 at % Ni-Mn/Ni-Fe films,J. of Magn. Magn. Mater., 171, 29.

[23] Nakatani, R., Hoshiya, H., Hoshino, K., Sugita, Y., 1997. Exchange coupling of (Mn-Ir, Fe-Mn)/Ni-Fe-Co and Ni-Fe-Co/(Mn-Ir, Fe-Mn) films formed by ion beam sputtering, IEEE Trans. Magn., 33, 3682.

[24] Nakatani,R., Hoshiya,H., Hoshino, K., Sugita,Y., Relationship between film structure and exchange coupling in Mn-Ir/Ni-Fe films, J. of Magn. Magn. Mater., 173, 321.

[25] Takano,K., Kodama,R.H., Berkowitz,A.E., Cao,W., Thomas,G., Interfacial Uncompensated Antiferro magnetic Spins: Role in Unidirectional Anisotropy in Polycrystalline Ni81Fe19/CoO Bilayers, Phys. Rev. Lett., 79, 1130.

[26] Umemoto, T., Maeda, A., Takahashi, S., Tanuma, T., Kume, M., 1997. Physical Properties of CoFe/IrMn Spin-Valves Prepared Using Ion Beam Sputtering with an Xe-H_2 Mixture Gas, Japanese, J. Appl. Phys., 36.

[27] Negulescu,B., Lacour,D., Montaigne,F., Gerken,A., Paul,J., Spetter,V., Marien,J., Duret,C.,Hehn,M. 2009. Wide range and tunable linear magnetic tunnel junction sensor using two exchange pinned electrodes, Appl. Phys. Lett., 95, 112502.

[28] Russak,M.A., Rossnagel,S.M., Cohen,S.L., McGuire,T.R., Scilla,G.J., Jahnes,C.V., Baker,J.M., Cuomo,J.J. 1989. MnFe and NiFe Thin Films and Magnetic Exchange Bilayers, J. Electrochem. Soc., 136, 179.

[29] Uneyama,K., Tsunoda,M., Konoto,M., Takahashi,M., 1997. Effect of Gas Adsorption onto the Interface on the Exchange-Coupling Field of Ni-Fe/25 at % Ni-Mn Film, J. Magn. Soc. Jpn., 21, 517.

[30] Issa, B., Obaidat, I.M., Albiss, B.A., Haik, Y. 2013. Magnetic nanoparticles: surface effects and properties related to biomedicine applications, Int. J. Mol. Sci., 14.

[31] Ehresmann, A., Koch, I., Holzinger, B. 2015.Manipulation of Superparamagnetic Beads on Patterned Exchange-Bias Layer Systems for Bio-sensing Applications, Sensors, 15.

[32] Moran,T. J., Gallego,J. M.,Schuller, I.K., 1995. Increased exchange anisotropy due to disorder at permalloy/CoO interfaces, J. Appl. Phys., 78, 1887.

[33] van der Zaag, P.J., Wolf,R.M., Ball,A.R., Bordel,C., Feiner,L.F., Jungblut, R.1995. A study of the magnitude of exchange biasing in [111] Fe3O4/CoO bilayers, J. of Magn. Magn. Mater., 148, 346

[34] Fujiwara, H., Nishioka, K., Hou, C., Parker, M.R., Gangopadhyay, S., Metzger, R.1996.Temperature dependence of the pinning field and coercivity of NiFe layers coupled with an antiferromagnetic FeMn layer, J. Appl. Phys., 79, 6286.

[35] Danan, H., Gengnagel, H., Steinert,J., Linzen,A. 1971. Exchange coupling investigations on epitaxial deposited and superficially oxidized Co and Ni monocrystalline films, Journal de Physique (France) 32, C1-131.

[36] Watanabe,K., Tadokoro,S., Kawabe, T., Fuyama, M.,Fukui, H., Narishige, S. 1994. Exchange-Biased Magnetoresistive Elements with Oxide Antiferromagnetic Thin Films, J. Magn. Soc. Jpn., 18.

[37] Schlenker, C. 1968. Couplage ferro-antiferro magnétique et traînage magnétique dans des couches minces multiples Co-CoO et Ni-NiO Par, Phys.Stat. Sol., 28, 507.

[38] Ball,A.R., Leenaers,A.J.G., van der Zaag,P.J., Shaw,K.A, Singer,B., Lind,D.M., FredrikzeH., RekveldtM.T. 1996. Polarized neutron reflectometry study of an exchange biased Fe_3O_4/NiO multilayer" Appl. Phys. Lett., 69.

[39] Borchers,J.A., Erwin,R.W., Berry,S.D., Lind,D.M., Ankner,J.F, Lochner,E., Shaw,K.A., Hilton,D. 1995. Long-range magnetic order in Fe_3O_4/NiO superlattices, Phys. Rev. B, 51.

[40] Lind,D.M., Borchers,J.A., Erwin,R.W., Ankner,J.F.,Lochner,E., Shaw,K.A., DiBari,R.C. Portwine,W., Stoyonov,P., Berry,S.D. 1994. Investigations of the interplay between crystalline and magnetic ordering in Fe_3O_4/NiO superlattices, J. Appl. Phys., 76, 6284.

[41] van der Graaf,A., Ball,A.R., Kools,J.C.S., 1997. Magnetic alignment in spin-valve system studied by polarized neutron reflectometry, J. of Magn. Magn. Mater. 165,479.

[42] Miltenyi,P., Gruyters,M., Guntherodt,G., Nogues,J., SchullerI, K. 1999. Spin waves in exchange-biased Fe/FeF_2,Phys. Rev. B, 59, 3333.

[43] Geoghegan,D.S., McCormick,P.G.,Street,R. 1995. Mechanically Alloyed Antiferro magnetic-Ferromagnetic Exchange Coupled Nano-Composites, Mater. Sci. Forum, 179-181.

[44] BeckP.A. 1978. Properties of mictomagnets (spin glasses), Prog. Mat. Sci.,23,1.

[45] Mydosh,J.A.1975. Spin glasses and mictomagnets, AIP Conference Proceedings, 24, 131.

[46] Razzaq, W.A., Wu, M.1991. Synthesis and magnetization of a reentrant Ni-Mn thin-film system, J. Appl. Phys., 69, 5078.

[47] Iwata,T., Kai,K., Nakamichi,T., Yamamoto,M. 1969. Exchange Anisotropy in Single Crystals of Cu-Mn Alloys, J. Phys. Soc. Jpn., 28.

[48] Singh, R., Ingal, B., Varga, L.K., Khovaylo, V.V., TaskaevS., Chatterjee R., 2015. Large exchange bias in polycrystalline ribbons of $Ni_{56}Mn_{21}Al_{22}Si_1$, J. of Magn. Magn. Mater.., 394.

[49] Singh, R., Ingal B., Varga L.K., Khovaylo V.V., TaskaevS., Chatterjee, R. 2014. Large exchange bias in$Ni_{55}Mn_{19}Al_{24}Si_2$ polycrystalline ribbons, Physica B, 448.

[50] Perzanowski, M., Krupinski, M., Zarzycki,D., Dziedzic, A., Zabila, Y., Marszalek, M., 2019. Exchange Bias in the $[CoO/Co/Pd]_{10}$ Antidot Large Area Arrays, ACS Applied Materials & Interfaces, 9.

[51] Suck,S. Y., Neu,V., Wolff,U., Bahr,S., Bourgeois,O., Givord,D., 2009. Magnetic force microscopy analysis of magnetization reversal in exchange-biased Co/CoO nanostructure arrays, Appl. Phys. Lett., 95.

[52] Alvarez, G. S., Geshev, J., Puig, S.A., Navau, C., Sanchez, A., Sort, J., Nogués, J., 2016.Tunable High-Field Magnetization in Strongly Exchange-Coupled Freestanding Co/CoO Core/Shell Coaxial Nanowires, ACS Applied Materials & Interfaces, 31.

[53] ShiDa-Wei, Javed, K., Ali, S.S., ChenJun-Yang, LiPei-Sen,Zhao, Y.-G., 2014. Exchange-biased hybrid ferromagnetic–multiferroic core–shell nanostructures, Nanoscale, 13.

[54] Tripathy,D., Adeyeye, A.O., Singh,N., Stamps,R L, 2009. Controlling the magnetization reversal in exchange-biased Co/CoO elongated nanorings, Nanotechnology, 20.

[55] Malozemoff,A.P., 1987. Random-field model of exchange anisotropy at rough ferromagnetic-antiferromagnetic interfaces, Phys. Rev. B, 35, 3679.

[56] Koon, N.C. 1997. Calculations of exchange bias in thin films with ferromagnetic/ antiferromagnetic interfaces,Phys. Rev. Lett., 78, 4865.

[57] Schulthess,T.C., Butler, W.H., 1998. Consequences of spin-flop coupling in exchange biased films, Phys. Rev. Lett., 81, 4516.

[58] Schulthess, T.C., Butler, W.H., 1999. Coupling mechanism in exchange biased films,J. Appl. Phys., 85, 5510.

[59] Takahashi,M., Yanai,A., Taguchi,S., Suzuki,T., 1980. A Study of Exchange Anisotropy in Co-CoO Evaporated Thin Films, Japanese J. Appl. Phys., 19, 1093.

[60] Smardz,L., Köbler,U., Zinn,W., 1991. Temperature and thickness dependence of unidirectional magnetic anisotropy effects in Co/CoO thin films, Vacuum, 42, 283.

[61] Chen,Y., Lottis,D.K., Dahlberg,E.D.,1991. Magnetotransport properties of iron thin films,J. Appl. Phys.,70, 5822.

[62] Chen,Y., Lottis,D.K., Dahlberg,E.D., 1991. Application of magnetic reorientation phase transition in the study of exchange anisotropy, Mod. Phys. Lett. B, 5, 1781.

[63] Hempstead,R.D., Krongelb,S., Thompson, D.A.,1978. Unidirectional anisotropy in nickel-iron films by exchange coupling with antiferro magnetic films, IEEE Trans. Magn., 14, 521.

[64] Greiner,J.H.,1966. Exchange Anisotropy Properties in Sulfided Iron Films, J. Appl. Phys., 37, 1474.

[65] Kuhlow,B., Lambeck,M., Schroeder-Fürst,H., Wortmann,J., 1971.Critical curves of thin ferromagnetic films with antiferromagnetic exchange coupling, Phys. Lett. A, 34.

[66] Park, C.M., Lee, K.A., Hwang, D.G., Lee, S.S., Kim, M.Y., 1997, Journal of Korean Physical Society, 31, p. 508

[67] Smardz,L., Köbler,U., Zinn,W.,1992. Oxidation kinetics of thin and ultrathin cobalt films, J. Appl. Phys., 71, 5199.

[68] Lin,X., Murthy,A.S., Hadjipanayi,sG.C., Swann,C., Shah,S.I., Magnetic and structural properties of Fe-FeO bilayers, J. Appl. Phys., 76, 6543.

[69] Chen,M.M., Tsang, C., Gharsallah, N., 1993. Exchange bias enhancement through interdiffusion of NiFe/FeMn/metal films, IEEE Trans. Magn., 29, 4077.

[70] Tsang, C., Lee, K.,1982. Temperature dependence of unidirectional anisotropy effects in the Permalloy-FeMn systems, J. Appl. Phys., 53, 2605.

[71] Toney,M.F, Tsang,C., Howard, J.K.,1991. Thermal annealing study of exchange-biased NiFe-FeMn films, J. Appl. Phys., 70, 6227.

[72] Matsumoto, M., Morisako,A., Takei,S., Taijima,S., 1997. Multilayering NiFe/FeMn Antiferromagnetic Coupling Films by Sputtering, J. Magn. Soc. Jpn., 21, 509.

[73] Nishioka, K., Hou, C., Fujiwara,H., Metzger,R.D., 1996.Grain size effect on ferro-antiferromagnetic coupling of NiFe/FeMn system,J. Appl. Phys., 80, 4528.

[74] WangS.X., BaileyW.E., 1997. Ion beam deposition and structural characterization of GMR spin valves,IEEE Trans. Magn., 33, 2369-2374.

[75] Park C.M., MinK.I., ShinK.H.,1996. Effects of surface topology and texture on exchange anisotropy in NiFe/Cu/NiFe/FeMn spin valves,J. Appl. Phys.,79, 6228.

[76] Lin T., Tsang C., Fontana R.E., Howard J.K.,1995. Exchange-coupled Ni-Fe/Fe-Mn, Ni-Fe/Ni-Mn and NiO/Ni-Fe films for stabilization of magnetoresistive sensors, IEEE Trans. Magn., 31, 2585-2590.

[77] Kishi H., Kitade Y., Miyake Y.,Tanaka A., Kobayashi K.,1996. Study of exchange-coupled bias field in Ni-Fe/Pd-Pt-Mn thin films,IEEE Trans. Magn., 32, 3380-3382.

[78] Lin, T., Gorman, G.L., Tsang C., 1996. Investigation on magnetic saturation in switched reluctance motor using 2D hybrid finite element method,IEEE Trans. Magn., 32, 4317-4319.

[79] Devasahayam, A.J., Mountfield, K.R., Kryder, M.H, 1997.Small track width MR sensors stabilized with NiMn, IEEE Trans. Magn., 33, 2881-2883

[80] Lederman, D., Nogués, J., Schuller, I.K., 1996. Positive Exchange Bias in FeF_2-Fe Bilayers, Phys. Rev. Lett.,76, 4624-4627.

[81] Lederman, D., Nogués, J., Schuller, I.K., 1997. Exchange anisotropy and the antiferromagnetic surface order parameter, Phys. Rev. B, 56, 2332-2335.